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14. ABSTRACT
This AFOSR/DURIP sponsored funding was used to upgrade the data acquisition, graphics and image processing capabilities of the Turbulence Research Laboratory (TRL) of the State University of New York at Buffalo. The proposed upgrades were of immediate benefit to the research sponsored by AFOSR (Investigation into the Dynamics of the Jet Mixing Layer) as well as a number of on-going and anticipated investigations. The AFOSR sponsored effort enhanced on-going research using 138 hot-wire probes to investigate the dynamics of the jet mixing layer. The hot-wires are used to obtain simultaneous data at 138 positions so that the instantaneous velocity profiles can be reconstructed using the proper orthogonal decomposition (POD). The complexity of the data acquisition required for this number of probes has been considerably simplified. In spite of this, the demands on the data acquisition system and the experimenter are enormous, especially with regard to calibration and post-data-acquisition validation, visualization and processing of the data.

The equipment purchased both addressed the immediate research needs, and considerably enhanced the ability of the Turbulence Research Laboratory to meet the needs of the university and regional technical community.

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Experimental Data Acquisition and Quantitative Visualization of Turbulent Jet Mixing Layers

Final Report

William K. George

Abstract

This AFOSR/DURIP sponsored funding was used to upgrade the data acquisition, graphics and image processing capabilities of the Turbulence Research Laboratory (TRL) of the State University of New York at Buffalo. The proposed upgrades were of immediate benefit to the research sponsored by AFOSR (Investigation into the Dynamics of the Jet Mixing Layer) as well as a number of on-going and anticipated investigations. The AFOSR sponsored effort enhanced on-going research using 138 hot-wire probes to investigate the dynamics of the jet mixing layer. The hot-wires are used to obtain simultaneous data at 138 positions so that the instantaneous velocity profiles can be reconstructed using the proper orthogonal decomposition (POD). The complexity of the data acquisition required for this number of probes has been considerably simplified. In spite of this, the demands on the data acquisition system and the experimenter are enormous, especially with regard to calibration and post-data-acquisition validation, visualization and processing of the data.

The equipment purchased both addressed the immediate research needs, and considerably enhanced the ability of the Turbulence Research Laboratory to meet the needs of the university and regional technical community. A number of computational fluid dynamics analysis, flow visualization experiments, data visualization and theoretical modeling studies used this equipment on a regular basis.

The Supported Research

The backbone of the experimental program most significantly enhanced by this equipment acquisition was the large turbulent axisymmetric jet. This facility has been extensively used in the past by the Turbulence Research Laboratory in Buffalo, and is thoroughly described in dissertations of Citriniti [1], Jung [2] and Gamard [3].

A series of near field measurements by Jung [2] where extended to the far field by Gamard [3] using the same array of 138 long hot-wires. These were designed specifically to resolve the energetic features of the mixing layer of the jet in the potential core at 3 diameters downstream of the jet exit. The idea behind the design of the hot-wires array is to measure optimally the energetics of the flow. Knowing that the interest lies in the large scales, Citriniti and George [4] used the natural filtering length of the hot-wires as a small-scale filter. Indeed, the velocity measured by the wire is actually the average over its length. By increasing the wire length, the information in the small wavenumbers is averaged naturally before the signal is sampled, therefore avoiding any folding into other modes.

If it is assumed that spatial resolution is the principal limitation to the `apparent' frequency response, the maximum frequency that can be resolved by the hot wires can be estimated by: $f_c = U / 2l_w$ with $l_w = 1$ cm being the length of the wire, and U the velocity seen. Note that the temporal response of the wires can be estimated to be at least 10 μs, orders of magnitude faster than presented by the flow field (Citriniti [1]).

Using similarity predictions obtained from the models of Hussein *et al.* [5], we obtained the following frequencies: 850 Hz. to 312 Hz. for the 21D, 50 m/s and 69D, 70 m/s cases. To avoid any aliasing, we need to sample at, at least, twice that frequency, respecting the Nyquist criterion. For all our cases, we sampled at a frequency of 4,001.6 Hz. to be able to satisfy the sampling limitations of measuring all the signals together, as will be explained later. As seen from spectral

plots, the probes roll-off in the -5/3 range, long before the limiting frequency induced by the length of the wire, implying that the wire sees indeed most of the kinetic energy. It should be noted that Citriniti and George [6] also showed the one-dimensional spectrum to be affected at all wavenumbers, because of the reduced spatial aliasing intrinsic to the one-dimensional spectra.

The Hot-Wires Array

Based on the results of Glauser [7], it was concluded that the mixing layer needed 6 concentric radii in order to resolve correctly the dynamics using the POD. It was also seen that the azimuthal distribution was increased as one moves away from the centerline. Therefore, an array of 6 concentric radii of increasing azimuthal distribution, comprising a total of 138 hot-wires was created to fully resolve adequately the mixing layer, see Figure 1 and Figure 2. Each single wire was oriented in the azimuthal direction, using its long length as a natural filter to eliminate, without aliasing the higher azimuthal modes. Note that, since streamwise variations at small scales are convected by the probe, the temporal filtering accomplishes the same aliasing for the streamwise variations.

The hot wires, all home-made in the laboratory, were 1 cm. long and made of 12.7 μm unplated tungsten (Sigmund-Cohn, Mt. Vernon, NY), creating an actual l/d of around 800. Each wire was mounted on a 37 cm. long brass tube; all of them fixed and held together using a 50 cm. wide bicycle wheel. The electric cables were therefore 40 cm. away from the measuring position of the wires, minimizing therefore the actual influence on the wires of a blockage by the probe array. Using the smoke generator apparatus, a confirming check was made by Citriniti and George [4] as to the minimum of a blockage by the probe array on the measuring devices (see Figure 3).
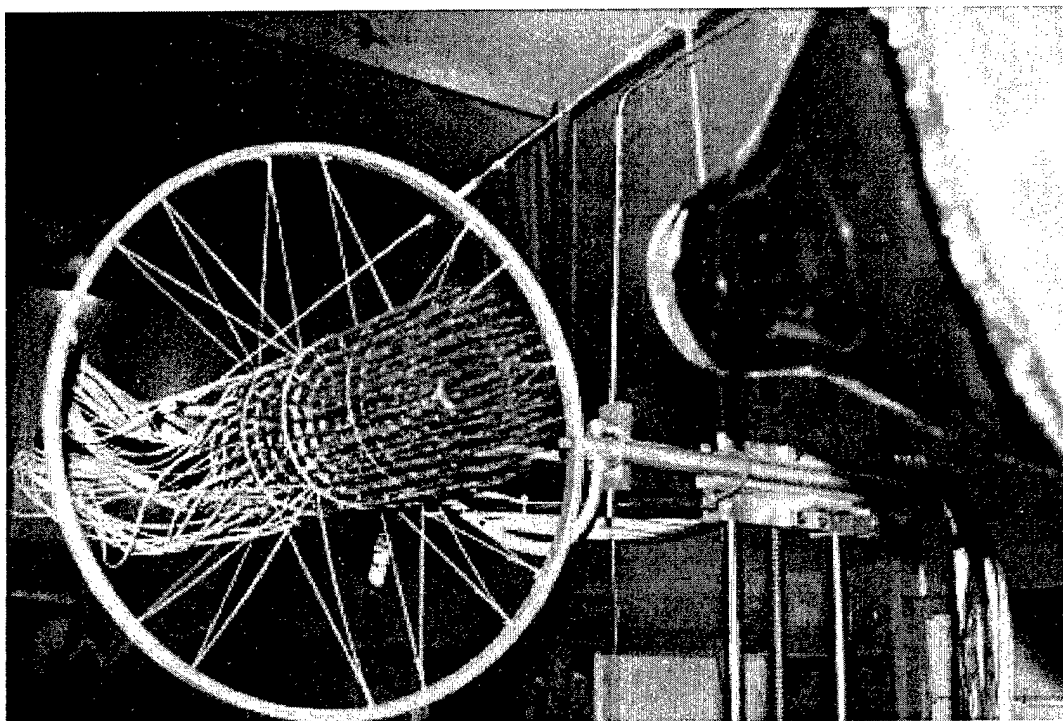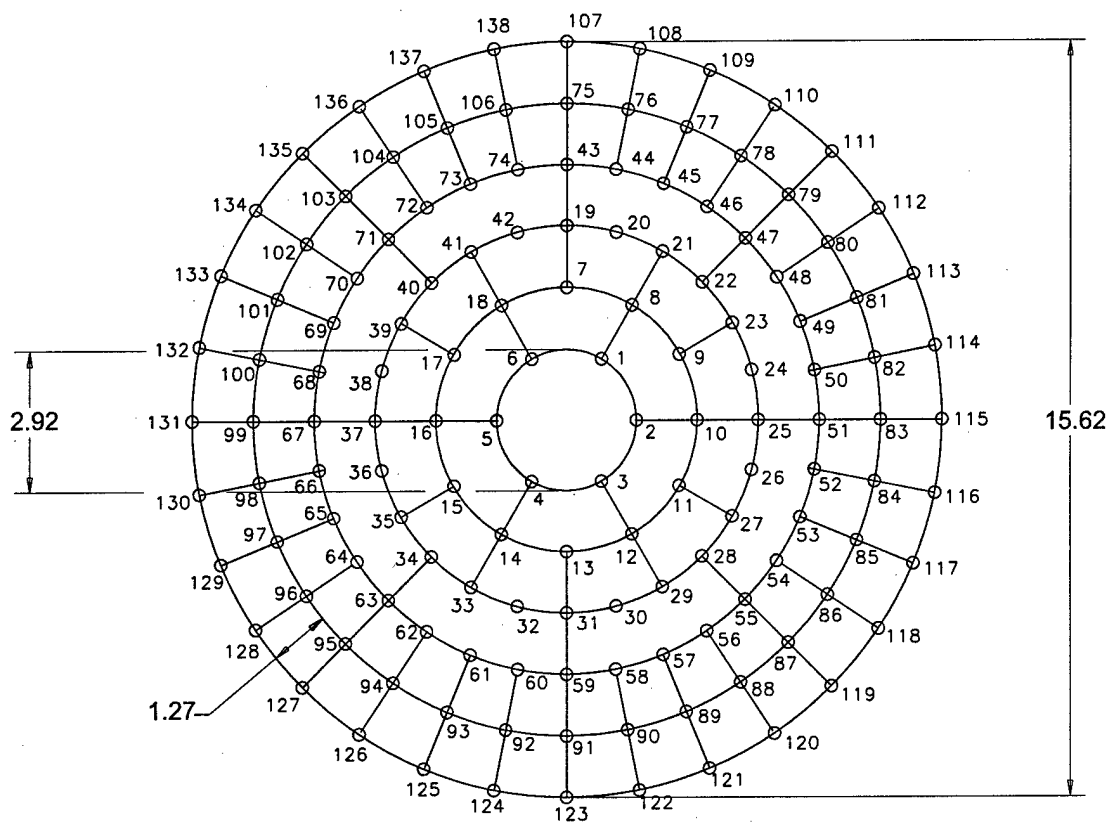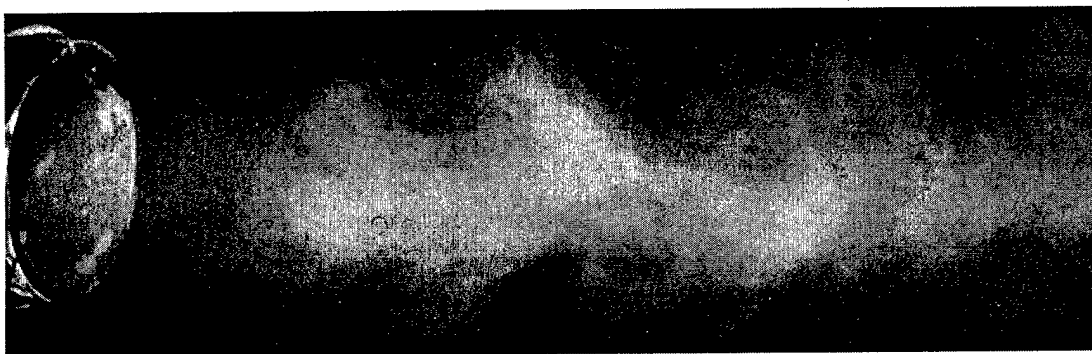

Figure 1. Picture of jet with 138 hot-wire probe array.

Figure 2. Schematic of the 138 hot-wire probe array. Each small circle represents a single hot-wire.

A

B

Figure 3. A) Single frame of smoke visualization recorded and edited using the purchased video recording and editing system. B) Smoke visualization of the flow field around the hot-wire array. Taken from Citirniti and George [6].

Acquiring the Data

The Acquisition Board

The huge constraint of the experiment was to acquire 140 signals (139 probes, and other monitoring signals) simultaneously at the right sampling frequency. We therefore used a data acquisition board from Microstar Laboratories DAP 5200a purchased with AFOSR-DURIP funding. It has an on-board operating system optimized for 32 bit operation in a PC expansion slot, consisting of an AMD K6-2 CPU with PCI bus interface, 14-bit A/D converter, with a 50 ns. acquisition time resolution, 800 K samples per second throughput, and programmable input and output voltage range.

The DAP 5200a, as seen on Figure 4 was connected via a 68-line round cable to an analog backplane interface board MSXB 029, itself located inside the anemometer rack and connected to 3 analog input Microstar Laboratories expansion cards of type MSXB 018. These expansion cards are connected in series to each other via 68-line flat ribbon cables, and each one holds 4 connectors each with 16 single-ended inputs. The 3 cards can therefore process up to a maximum of 3 X 4 X 16 =192 analog signals.
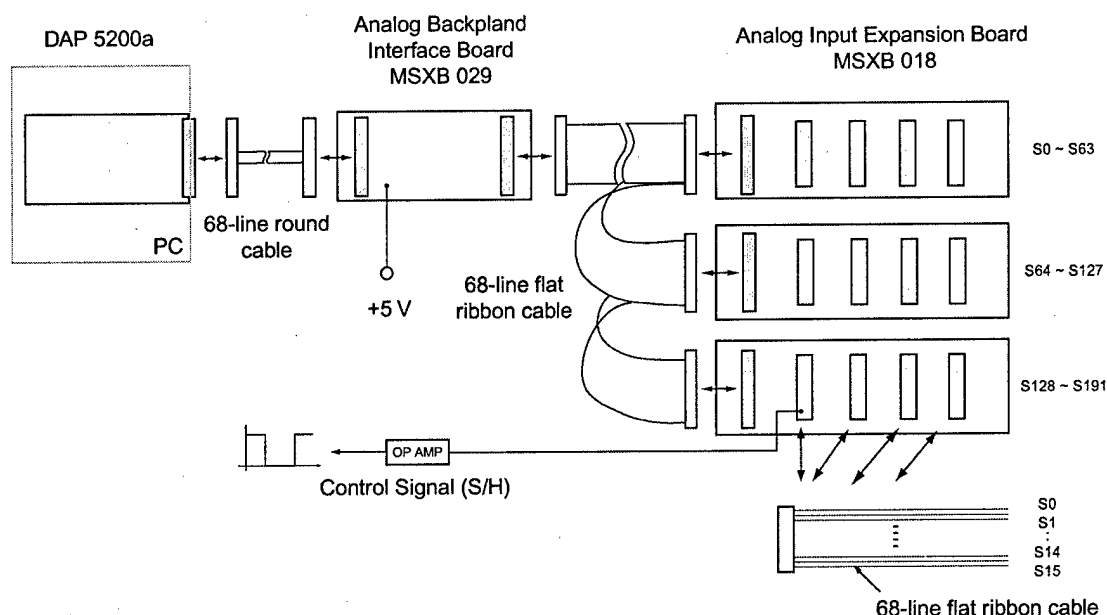
Figure 4. Schematic diagram of the Microstar DAP5200a Data Acquisition System.

Simultaneous Sampling

To obtain data simultaneously at all 138 positions, a sample/hold amplifier, SHC298, was used in each anemometer board separately. It had a 12 bit throughput accuracy, less than 10 μs acquisition time[1], wide-band noise less than 20 μV$_{rms}$, reliable monolithic construction and TTL-CMOS-compatible logic input features.

The positive-edge triggered control signal for the sample/hold amplifier is generated by the Microstar 5200a Data Acquisition Processor as part of the sampling process. The sampling time here is 10.2 μs and holding time 239.7 μs, so the resulting sampling frequency is 4,001.6 Hz (= 1/(10.2+239.7 μs)). When the mode control is switched from hold-mode to sample-mode with the positive-edge triggered signal, the sample/hold amplifier samples data at all 138 anemometers simultaneously and holds the signals until it switched to the next sample-mode. During the hold-mode, the Microstar DAP 5200a collects data from all the channels, and then saves them on the hard disk.

147 channels are used to acquire data from the hot wire probe array. They consist of the 139 channels for the hot wire probes, a channel for the pressure transducer, and one for room temperature, and 6 channels for generating the control signals. The holding time of 239.7 μs was calculated using 141 ch X 1.7 μs, and the sampling time of 10.2 μs from 6 ch X 1.7 μs. The sampling time 1.7 μs for each channel is selected accordingly with the optimal sampling frequency, 4,000 Hz. The resulting control signal is generated automatically by the Microstar DAP 5200a while operating, and is applied to all sample/hold amplifiers at each anemometer separately as the positive-edge trigger signal within the standard TTL logic ranges from 0 to +5 volts.

Calibration of the Wires

Calibration of even a single probe is not easy, even if straightforward. Calibration of 139 probes is

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[1] It is the required time for the sample/hold output to settle within a given error range of its final value,when switched from Hold to Sample.

a monumental task. Fortunately, drift during the experiment was not a problem. And we had the advantage of considerable experience in the Citriniti and George [4] experiment.

Conversion of the voltage acquired by the probes to velocity is done by first exposing the probes to a known velocity and computing the calibration conversion curve. The high stability of the anemometers allowed a high reproducibility of the signal, therefore only one calibration was necessary, although this was checked at the end of the experiment.

The calibration curve was modeled by a 4th-order polynomial: $Vel^{0.5} = a_0 + a_1 Volt + a_2 Volt^2 + a_3 Volt^3 + a_4 Volt^4$ Mainly because the linearity of the method removes unwanted sources of errors from mathematical roundoffs both when computing the coefficients initially with the calibration scheme and when recovering the velocity from the acquired voltage in the experimental stage. The order of the polynomial has been chosen after previous trials done in the Turbulence Research Laboratory.

We calibrated 20 to 30 wires at the same time by placing them at a radius away from the jet exit in the laminar core of the flow; the boundary layer at this point was small and the velocity profile was constant within 0.1%. A collection of the voltage outputs from those wires was acquired along with the signal from the pressure transducer at a frequency of 4,001.6 Hz. and a sampling time of 100 s. The velocity of the jet was in the range of 0 to 25 m/s., which was the predicted range later seen by the wires in experimental configuration. A sample of a calibration curve is seen in Figure 5.
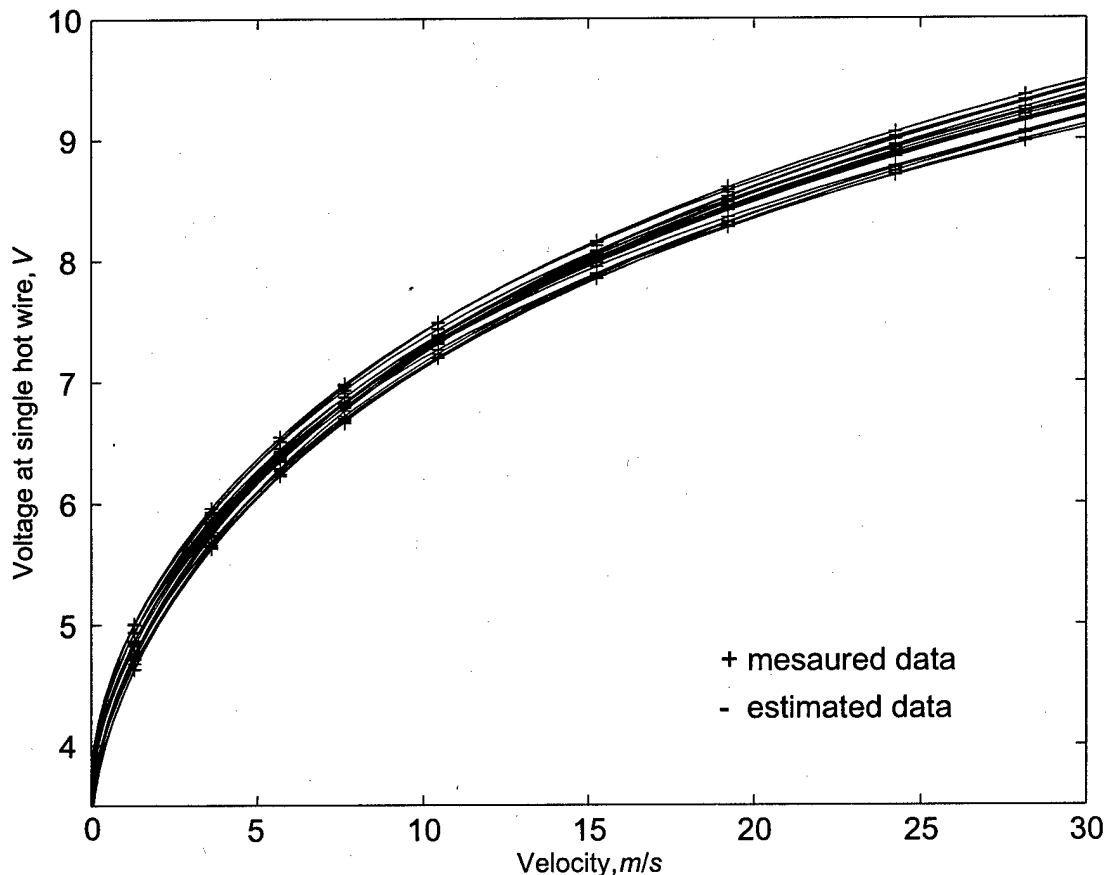

Figure 5. Calibration curve for a polynomial fit. Symbols are measured data points

The Experimental Results

All of the calibration data acquisition and processing was performed on the AFOSR-DURIP funded data acquisition system. The subsequent data processing was performed on the data visualization workstation. The large-scale structure of an axisymmetric mixing layer was investigated using the POD for Reynolds numbers of 78,400, 117,600, and 156,800 at x/D=2.0 to 6. Data were sampled simultaneously at all measuring positions at 4,001.6 Hz for 400 sec using 139 hot-wire probes of length of 1 cm. The sampling frequency was sufficient to satisfy the temporal Nyquist criterion. The record length of each block of data was 4,096 samples giving a bandwidth of 0.98 Hz and a length of 1.02 sec. In all, 388 blocks were used in the statistical analysis, which reduced the variance of the cross-spectra to less than 5%. The Strouhal number of the spectral peak was in the range of 0.25 to 0.5 for all downstream locations.

In addition to applying the POD in the radial direction, the streamwise velocity at each cross-section was decomposed into Fourier modes by both azimuthal mode and temporal frequency. The variations due to downstream positions and Reynolds numbers were discussed in detail. The original velocity field was also reconstructed using only the first POD mode and selected azimuthal modes using a linear combination of the coefficients and eigenfunctions. From animations of the reconstruction, the interaction between the azimuthal modes and the dynamics of the coherent structure could be visualized.

Similarity of the energy distribution

From application of the POD in the radial direction, it was observed that the first POD mode contains more than 60% of turbulent energy at all downstream positions and Reynolds numbers. The first 2 POD modes contain more than 80%.

The eigenvalues have a strong dependence on the streamwise position, x/D. And mode-0 behaves in a manner entirely different than the higher modes. The main results are as follows:

1. The energy in mode-0 moves to lower frequencies as x/D increases, and the total energy in mode-0 decreases. (Note that because the flow is largely correlated by the probes, frequency is to more correctly representative of wavenumber, $k = 2\pi f / U_c$) Corresponding to the diminution of mode-0 is the emergence of mode-1. This is consistent with an approach toward homogeneity in the downstream direction, and suggest that perhaps some residual value may control (or reflect) the growth rate of the far jet.

2. The behavior of mode-0 and mode-1 as x/D increases is similar to that predicted from inviscid instability theory. In particular, Batchelor and Gill [8] show that for a top-hat profile all modes are unstable, but mode-0 grows the fastest. By contrast, once the profile is fully-developed, mode-0 is stable, and mode-1 grows the fastest, at least for a parallel flow. Similar conclusions were reached by Michalke [9] and Michalke [10] as well, but for spatially growing disturbances. These stability results are strikingly similar to the behavior of the POD modes which have the most energy and even the eigenfunctions appear to be similar.

3. The energy distribution (with azimuthal mode number and frequency) of the first, second, and third POD modes has a strong dependence on x/D.

4. For azimuthal mode greater than m=0, the energy shifts from higher modes to lower modes (m>0) as x/D increases. In fact, the eigenspectra collapse when scaled in shear layer similarity variables; i.e. $\lambda / x U_0^2$ versus fx/U_0 and mx/D.

5. The energy distribution of the first POD mode has no dependence on Reynolds numbers over the range of these experiments. This is contrary to the suggestion of \cite{HLB96} that more complicated modal structures might evolve with increasing Reynolds number.

On the other hand, this observation is consistent with suggestion by Glauser [7] and Citriniti and George [4] that once the Reynolds number is sufficiently high, there should be no dependence.

6. The Strouhal number associated with the frequency of maximum energy of the eigenspectra of the first POD mode correlates well with Strouhal number of the velocity spectral peak.

The velocity reconstructions

The instantaneous fluctuating velocity field at each cross-section was reconstructed using the eigenfunctions and coefficients obtained from the projection onto the original instantaneous velocity measured by all of the probes (in the manner of Citriniti and George [4]). From the animations of the velocity field, these main characteristics were observed:

1. Near the jet exit, highly organized and near-periodic evolutions of the large-scale structures are observed.

2. Azimuthally coherent vortex rings, the volcano-like eruptions identified by Citriniti and George [4], dominate the dynamics and the interactions of the structures until about $x/D \sim 4$.

3. The passage frequency for the volcanic eruption reasonably matches with the Strouhal frequency and 0th mode frequency in the range of $x/D = 2$ to 4.

4. Beyond $x/D \sim 4$, the volcano-like eruptions die off rapidly.

5. For $x/D \geq 4$, a "propeller-like" structure appears and dominates the pattern. For this experiment, at least, this "propeller-like" structure appears to rotate in a single direction. The direction of this rotation corresponds to the direction of a slight (1:1000) rotation at the exit plane of the jet, but the rate of rotation of the "propeller" is orders of magnitude faster.

Publications and Activities Benefiting from this Funding

Post Graduate Degrees
1. S. Gamard. A new similarity analysis for the turbulence energy spectrum. Master's thesis, University at Buffalo, 1999. [11]
2. M. Wosnik. On wall-bounded turbulent shear flows. PhD thesis, University at Buffalo, September 2000. [12]
3. Scott H. Woodward. Progress toward a massively parallel thermal anemometry system. Master's thesis, University at Buffalo, September 2001. [13]
4. Asad M. Sardar. HVAC Final Word. PhD thesis, University at Buffalo, May 2001. [14]

Publications and Presentations
1. J. H. Citriniti and W. K. George. Reconstruction of the global velocity field in the axisymmetric mixing layer utilizing the proper orthogonal decomposition. Journal of Fluid Mechanics, 418:137-166, 2000.
2. D. Ewing and W. K. George. The effect of cross flow on the mean square derivatives measured using hot wires. Expts. in Fluids, 29:418-428, 2000.
3. D. Ewing and S. H. Woodward. Evaluating the accuracy of the LSE-POD technique in an axisymetric shear layer. In European Turbulence Conferance, Madrid, Spain, 2000.
4. Dan Ewing and Scott H. Woodward. On accurate experimental measurements of the dynamics of large scale structures in turbulent flows. In IUTAM, Symposium on Turbulent Mixing and Cumbustion, Queen's University, Kingston, ON, CA, Jun 2-6 2001.
5. Daniel Ewing, Scott H. Woodward, and Joseph H. Citriniti. The accuracy of applying lumley's pod to instantaneous fields computed using stochastic estimation. In The

TurbulentYears: John Lumley at 70, June24-25 2001. A Symposium in honor of John L. Lumley on his 70th Birthday.

6. Stephan Gamard, William K. George, Daehan Jung, and Scott H. Woodward. Application of a "slice" proper orthogonal decomposition to the far field of an axisymetric turbulent jet. *Physics of Fluids*, 14(7):2515-2522, July 2002.

7. Peter Johansson and W. K. George. Application of equilibrium similarity analysis on the axisymmetric wake. In *IUTAM Symposium on Bluff Body Wakes and Vortex-Induced Vibrations*, Marseille, France, June13-16 2000. IUTAM.

8. Daehan Jung, Stephan Gamard, Scott H. Woodward, and William K. George. Further investigation of the jet mixing layer using a 138 hot-wire probe and the pod. In *IUTAM, Symposium on Turbulent Mixing and Cumbustion*, Queen's University, Kingston, ON, CA, June2-6 2001.

9. Asad M. Sardar, Jr. William K. George, James R. Sonnenmeier, and Scott H. Woodward. Flow visualization study of an HVAC module operated in water. *Transaction of Society of Automotive Engineers*, VTMS-082, 2001.

10. Scott. H. Woodward, Dan Ewing, and Lars Jernqvist. Anemometer system review. In *In Sixth Annual Symposium on Thermal Anemometry*, Melbourne, AU, January 8-10 2001.

11. George, William K., *Effect of upstream conditions on turbulent boundary layers*. Dept. of Mechanics, KTH, Stockholm, Sweden, November 10, 2000.

12. George, William K., *Some new ideas for turbulent wall-bounded flows*. Dept. of Mathematics, U. of Oslo, Oslo, Norway, June 1, 2001.

13. Wosnik, Martin, *Experiment and Theory of Turbulent Flows: 1. The twodimensional wall jet, 2. Outlook/preview of planned experiments/facilities*. Department of Mechanical and Industrial Engineering, University of Toronto, Canada, May 17, 2001.

14. Wosnik, Martin, *Turbulence Research: Similarity Theory and Large Scale Experiments*. Boundary Layer Wind Tunnel Laboratory & Advanced Fluid Mechanics Research Group, University of Western Ontario, London, Ontario, Canada, July 26, 2001.

15. Castillo, Luciano and George, William K., *Similarity Analysis for Turbulent Boundary Layer with Pressure Gradient: Outer Flow*. AIAA Journal (2001), vol. 39, no.1, pp. 41–47.

16. Citriniti, Joseph H. and George, William K., *Reconstruction of the global velocity field in the axisymmetric mixing layer utilizing the proper orthogonal decomposition*. Journal of Fluid Mechanics (2000), vol. 418. pp. 137–166.

17. Ewing, Daniel and. George, William K., *The effect of cross-flow velocity on mean-square derivatives measured using hot wires*. Experiments in Fluids (2000), vol. 29, no. 5, pp. 418 – 428.

18. Gamard, Stephan and George, William K., *Reynolds number dependence of energy spectra in the overlap region of isotropic turbulence*. J. of Flow, Turbulence and Combustion (2000), vol. 63, pp. 443 - 477.

19. George, William K., Abrahamsson, Hans, Eriksson, Jan, Karlsson, Rolf I., Löfdahl, Lennart and Wosnik, Martin, *A similarity theory for the turbulent plane wall jet without external stream*. Journal of Fluid Mechanics (2000), vol. 425, pp. 367-411.

20. Glauser, M.N., Taylor, J.A., Ukeiley, L.S., George, W.K., and Citriniti, J.H., *A low dimensional description of the axisymmetric turbulent jet: an update*. ERCOFTAC Bull. (2000), 46, 53 – 61.

21. Wosnik, Martin and George, William K., *A theory for turbulent pipe and channel flows*. Journal of Fluid Mechanics (2000), vol. 421, pp. 115 – 145.

22. Gamard, Stephan, Jung, Daehan, Woodward, Scott and George, William K., *Application of a `Slice POD' to the Far Field of an Axisymmetric Turbulent Jet*. Submitted to Physics of Fluids, Aug. 2001.

23. Johansson, Peter and George, William K., *On the Effect of Finite Reynolds Number and Initial Conditions on the Axisymmetric Wake*. Submitted to Physics of Fluids, Aug. 2001.

24. Johansson, Peter and George, William K., *Application of the POD to the Axisymmetric Turbulent Wake behind a Disk*. Submitted to Physics of Fluids, Aug. 2001.

25. Jung, Daehan, Gamard, Stephan, Woodward, Scott H. and George, William K., *Further Investigation of the Jet Mixing Layer Using a 138 Hot-wire Probe and the POD*. To appear in volume of selected papers from the IUTAM meeting on Turbulent Jets in

Combustion, Queens U., Kingston, ON, Canada, June 11 – 14, 2001.

26. Wang, Honglu and George, William K., *The integral scale in homogeneous, isotropic turbulence*. Accepted for publication in J. Fluid Mechanics.

27. Wosnik, M. and George, W. K., *Reconciling the Zagarola/Smits Scaling and the George/Castillo Theory for the Velocity Deficit*. Submitted to AIAA Journal.

28. Abrahamsson, Hans, Eriksson, Jan, Karlsson, Rolf I., Johansson, Bert and George, William K., *Evaluation of Hot-Wire Errors in a Plane Turbulent Wall Jet*. ASME Sixth International Thermal Anemometry Symposium , Melbourne, Australia, Jan. 8-10, 2001.

29. Castillo, Luciano, Johansson, T. Gunnar, Walker, David J., Hangan, Horia, Blissitt, Mark and Seo, Junghwa, *Turbulent Boundary Layer at Very High Reynolds Number and Its Relation to the Initial Conditions*. Paper number AIAA-2001-2913, 31st AIAA Fluid Dynamics Conference, Anaheim, CA June 2001.

30. Castillo, Luciano, George, William K. and Wang, Xia, *Characterizing Turbulent Boundary Layers Subject to Strong Adverse Pressure Gradient with Eventual Separation*. Paper presented at the ASME Fluids Engineering Division Summer Meeting 2001, Separated and Complex Flows Symposium, S-315 FEDSM 2001-18112, New Orleans, LA, USA, June 2001.

31. Castillo, Luciano and Johansson, T. Gunnar, *Effect of Initial Conditions on the Zero-Pressure Gradient Turbulent Boundary Layer*. Poster presentation at: The Turbulent Years: A symposium honoring Professor John Lumley on the occasion of his 70th birthday, Cornell U., Ithaca, NY, June 24 –25, 2001.

32. Gamard, Stephan, Jung, Daehan, Woodward, Scott H. and George, William K., *Further investigation of the jet mixing layer using a 138 hot-wire probe and the POD*. 1000 Island Fluids Meeting, Gananoque, Canada, May 2001.

33. Gamard, Stephan, Jung, Daehan, Woodward, Scott H. and George, William K., *Further investigation of the jet mixing layer using a 138 hot-wire probe and the POD*. Svenska Mekanikdagar, Linköping, June 11-13, 2001.

34. George, William K., Johansson, Peter, Jung, Daehan, Gamard, Stephan and Woodward, Scott H., *Some Implications of Recent POD Studies for Control of Free Shear Flows*. Presentation at ERCOFTAC SIG 33 Workshop on Flow Control, Abisko, Sweden, April 25-27, 2001.

35. George, William K., Jung, Daehan, Gamard, Stephan, Johansson, Peter, and Woodward, Scott, *Applications of the POD to turbulent free shear flows*. Presentation at: The Turbulent Years: A symposium honoring Professor John Lumley on the occasion of his 70th birthday, Cornell U., Ithaca, NY, June 24–25, 2001.

36. Johansson, Peter, Woodward, Scott H. och George, William K., *Tillämpning av POD av turbulent vak bakom en circulär skiva*. Svenska Mekanikdagar, Linköping, June 11-13, 2001.

37. Johansson, Peter and George, William K., *On the Effect of Finite Reynolds Number and Initial Conditions on the Axisymmetric Wake*. Paper presented at the Second Int. Symp. on Turbulence and Shear Flow Phenomena, KTH, Stockholm, June 27-29, 2001.

38. Jung, Daehan, Gamard, Stephan, Woodward, Scott H. and *George, William K., Further Investigation of the Jet Mixing Layer Using a 138 Hot-wire Probe and the POD*, IUTAM meeting on Turbulent Jets, Queens U., Kingston, ON, Canada, June 11 – 14, 2001.

39. Jung, Daehan, Gamard, Stephan, Woodward, Scott H. and *George, William K., An investigation of the Reynolds-number dependence of the axisymmetric jet mixing layer using a 138 hot-wire probe and the POD*, 1000 Island Fluids Meeting, Gananoque, Canada, May 2001.

40. Karlsson, Rolf. I., George, William K., Johansson, Bert, Johansson, T. Gunnar, Woodward, Scott H., & Wosnik, Martin, *En Nordisk Vindtunnel För Turbulensforskning*. Svenska Mekanikdagar, Linköping, June 11-13, 2001.

41. Sardar, Asad. M., George, William. K., Sonnenmeier, James R. and Woodward, Scott H., *Flow visualization study of an HVAC module operated in water*. Paper presented at 2001 Vehicle Thermal Management Systems Conference and Exhibition, paper number. VTMS-082.

42. Johansson, Peter and George, William K., *Applications of equilibrium similarity analysis*

to the axisymmetric wake, 53rd Annual Meeting of the Fluid Dynamics Division of American Physical Society, Bulletin of the American Physical Society, ME 5, Vol. 45, No. 9, p. 164, 2000.

43. Johansson, T. Gunnar and Castillo, Luciano, *LDA measurements in a low to moderate Reynolds number flat plate boundary layer experiment.* 53rd Annual Meeting of the Fluid Dynamics Division of American Physical Society, Bulletin of the American Physical Society, MC 1,Vol. 45, No. 9, p. 158, 2000.

44. Wang, Honglu and George, William K., *Effect of box-size on integral scales in isotropic turbulence.* 53rd Annual Meeting of the Fluid Dynamics Division of American Physical Society, Bulletin of the American Physical Society, PB 2,Vol. 45, No. 9, p. 182, 2000.

45. Wang, Honglu, Sonnenmeier, James R., Gamard, Stephan and George, William K., *Evaluating DNS simulations of isotropic decaying turbulence using similarity theory.* ICTAM symposium, Chicago, IL, August 27-September 2, 2000.

46. Wosnik, Martin and George, William K., *Improvements to the George/Castillo Boundary Layer Theory.* 53rd Annual Meeting of the Fluid Dynamics Division of American Physical Society, Bulletin of the American Physical Society, AC 7, Vol. 45, No. 9, p. 14, 2000.

Summary of Purchased Equipment

Description	Proposed Cost	Actual Expenditure
Data Acquisition, Collection and Storage System		
Analog Data Acquisition System	$15,822	$14,629
Data Acquisition Software	$2,269	$2,318
Data Server/Storage Computer System	$6,397	$6,367
Matlab Data acquisition Toolbox	$199	$199
Data Processing and Visualization System		
Visualization Workstations	$19,050	$19,498
Matlab Data Processing Software	$1,993	$2,029
Digital Video Flow Visualization System		
Professional Video Recorder	$4,995	$5,643
Professional Video Editing System	$2,995	$1,720
Adobe Imaging and Illustration Software	$349	$324
Digital Video Editing Software	$1,498	$1,334
Total Budget Expenditures	$55,567	$54,062
Total DURIP Funding	$55,367	

Bibliography

1.   Citriniti, *Experimental Investigation Into the Dynamics of the Axisymmetric Mixing Layer Utilizing the Proper Orthogonal Decomposition*, in *Mechanical and Aerospace Engineering*. 1996, University at Buffalo: Buffalo.

2.   Jung, D., *An investigation of the Reynolds-number dependence of the axisymmetric jet mixing layer using a 138 hot-wire probe and the POD*, in *Mechanical and Aerospace Engineering*. 2001, University at Buffalo: Buffalo. p. 195.

3.   Gamard, S., *Application of the Slice POD to the Far Region of the Axisymmetric Jet*, in *Mechanical and Aerospace Engineering*. 2002, University at Buffalo: Buffalo. p. 169.

4.   Citriniti, J.H. and W.K. George, *Reconstruction of the global velocity field in the axisymmetric mixing layer utilizing the proper orthogonal decomposition*. Journal of Fluid Mechanics, 2000. **418**: p. 137-166.

5.   Hussein, H.J., S.P. Capp, and W.K. George, *Velocity Measurements in a High-Reynolds-Number, Momentum-Conserving, Axisymmetric, Turbulent Jet*. Journal of Fluid Mechanics, 1994. **258**: p. 31-75.

6.   Citriniti, J.H. and W.K. George, *The reduction of spatial aliasing by long hot-wire anemometer probes*. Experiments in Fluids, 1997. **23**(3): p. 217-224.

7.   Glauser, M.N., *Coherent Structures in the Axisymmetric Turbulent Jet Mixing Layer*, in *Mechanical and Aerospace Engineering*. 1987, University at Buffalo: Buffalo.

8.   Batchelor, G.K. and E.A. Gill, *Analysis of the instability of axisymmetic jets*. Journal of Fluid Mechanics, 1962. **14**: p. 529-551.

9.   Michalke, A., *On spatially growing disturbances in an inviscid shear layer*. Journal of Fluid Mechanics, 1965. **23**(3): p. 521-544.

10.   Michalke, A., *Survey on jet instability theory*. Prog. Aerospace Science, 1984. **21**: p. 159-199.

11.   Gamard, S., *A new similarity analysis for the turbulence energy spectrum.*, in *Mechanical and Aerospace Engineering*. 1999, University at Buffalo: Buffalo, NY.

12.   Wosnik, M., *On wall-bounded turbulent shear flows*, in *Mechanical and Aerospace Engineering*. 2000, University at Buffalo: Buffalo, NY.

13.   Woodward, S.H., *Progress Toward a Massively Parallel Thermal Anemometry System*, in *Mechanical and Aerospace Engineering*. 2001, University at Buffalo: Buffalo. p. 41.

14.   Sardar, A., *Cetrifugal Fans: Similarity, Scaling Laws, and Fan Performance*, in *Mechanical and Aerospace Engineering*. 2001, University at Buffalo: Buffalo, NY. p. 398.